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Scientific Objectives and Observational Requirements of Spectrometers for Main Belt Comet 133P/Elst-Pizarro Exploration

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ABSTRACT

The discoveries of main belt comets (MBC) in early twentieth century have attracted great interests of the planetary society, as the water ice and other volatile rich MBCs are located in the main belt and thus may have played a fundamental role in supplying waters to the early Earth. Therefore, MBCs are very interesting and important candidate objects for near future deep space exploration missions. We first summarize the scientific objectives of visible and infrared spectrometers for a flyby mission. Then we propose the major technical specifications for the spectrometers, based on the optical and thermal properties of one of the major targets, 133P/Elst-Pizarro. Our proposed spectral coverage is from 0.4 to 50 μm, which is realized by two spectrometers covering 0.4-5 μm and 5-50 μm, respectively. Visible and infrared imaging spectrometer (VIIS) is a grating spectrometer covering 0.4 to 5 μm with a spectral resolution of 5 nm in the VIS/NIR band and 10 nm in the SWIR/MWIR band. The spatial resolution of the VIIS is 0.5 m at an observational distance of 5 km. The signal to noise ratio of the spectrometer is better than 100 using cryogenic optics technology. Thermal emission spectrometer (TES) is a time modulated Fourier transform spectrometer which covers5-50 μ mby one single interferometer. The spectral resolution of TES is 8 cm^{-1}. The spatial resolution of TES is 10 m at an observational distance of 5 km.

Keywords: main belt comets 133P; reflectance spectrum; emission spectrum; spectrometer

1. INTRODUCTION

There are huge amounts of asteroid comets in solar system. They are also called small bodies. There are about 2000 asteroids larger than 1 km in diameter, about 300,000 larger than 100 meters in diameter, which are the planetary bodies formed 460 million years ago, containing a large amount of information on early formation and evolution of the solar system. The mineral content and distribution data of asteroid surface are the preconditions for the study of asteroid geological evolution, the origin of life and the exploitation and utilization of asteroid resources in the future. Some information such as exact orbital data and basic physical properties have been known by optical and radar observation from the ground. A lot of physical, chemical characteristics and minerals properties have been known by studying meteorites, the counterpart of the asteroids. Restricted by the detection accuracy and limitation of the methods, only some physical parameters of large asteroids can be measured from the ground, but the observation for those whose diameter are below sub kilometer is difficult. Through asteroids explorations, understanding the formation and evolution of the planetary system, origin of the solar system and life, further utilization of asteroids resource, have become the hot pots of many countries' space plan[1].

Human's 244 deep space exploration missions have almost covered all kinds of celestial bodies in the solar system, such as the moon, the seven planets and their satellites, dwarf planets, asteroids and comets. According to the exploration frequency of the past 20 years, the hot spots of planetary science research in the present and future are the Mars, asteroids and the moon. At the same time as the moon and Mars exploration boom, the asteroid exploration also gets people's attention. The exploration missions have developed from the early close flight to low altitude orbital exploration, and to the recently soft landing and sample return of asteroids.

Since the 21st century, the United States, Russia, Europe and Japan have made the long-term planning and schedule of the exploration. Deep space exploration has become one of the main development direction of space activities in the world.

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China has issued the white paper on space. In the paper, the government has stressed the deep space exploration. Deep space exploration is also included in the "Key projects of 2030 Scientific and Technologic Innovation". China Academy of Space Technology has started the pre-search of asteroid exploration by self-fund. Mission concept is proposed, which is divided into two phased, including sample return from one near earth asteroid and investigation of on main-belt comet. The comet is 133P/Elst-Pizarro[2].

2. ANALYSIS OF MAIN BELT COMET 133P/ELST-PIZARRO

133P/Elst–Pizarro is a rather strange object that has defined classification as an asteroid or as a comet and has a dual designation. It is characterized by exhibiting during a short period of time post perihelion, a tail without a coma. Marsden linked it with a previously known asteroid, 1979 OW7. It has been observed only in two apparitions. The discovery took place in 1996 and the coverage was sparse. In 2002 it was observed again and many of its physical properties were determined by Hsieh et al. [3] [4], which may be considered as the most complete study of this object to date.

The type of 133P may be F[5] class or B[6]class. Fig. 3 summarizes the observation results of 133P and compares the spectra with F type asteroids. Fig. 3a compares observation results of 133P with asteroid No. 419 and No. 704 in visible band[7] and near infrared band[6]. Fig. 1bgives the infrared band from 2um to 30um[8], which bases on thermal model and observation results. From the figure, we can conclude that 133P has an obvious absorption peak at 0.4um. But other F type asteroids lack of this obvious absorption characteristics. For band 2-4um, it mixes the solar reflection and thermal emission. For greater than 4um, it likes the plank black-body radiation. So if the temperature should be determined, the spectral range should no less than 30um. The spectral test shows that the spectral range should extend to 30um in order to determine the size of minerals according to the spectral test of silicate[9].

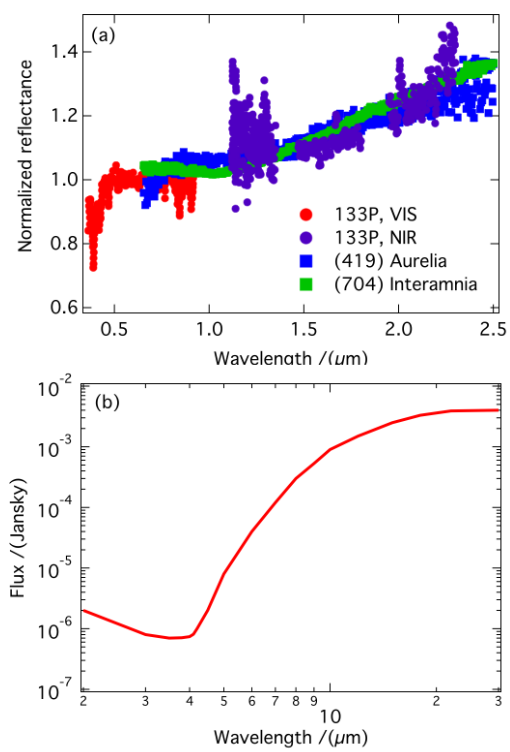

Fig.1 (a)Visible (VIS) and near infrared (NIR) reflectance spectra of 133P/Elst-Pizarro and that of two F-bodies (419) Aurelia and (704) Interamnia; data are from PDS Small Body Node https://pdssbn.astro.umd.edu/. (b) Thermal emission model spectra of 133P/Elst-Pizarro, data are from Bauer et al. 2012.

3. DESIGN OF SPECTROMETERS FOR MAIN BELT COMET 133P/ELST-PIZARRO

3.1 DESIGN OF VISIBLE AND INFRARED IMAGING SPECTROMETER

Visible and infrared imaging spectrometer has become a kind of necessary payload for material composition detection of deep space exploration mission. On account of its wide spectra coverage, high spatial resolution and high spectral resolution, this kind of spectrometer have been employed on Cassini, Mar Express, Rosetta, Venus Express, Dawn and many other deep space exploration missions. The small solar system bodies exploration mission will complete the flying off, landing, sampling of a near earth asteroid and flying around a comet, and returning to the earth. The mission for the spectrometer is to investigate the surface minerals in detail, to analyze the hardness of the surface, to choose the landing site, and to determine the composition of the main belt comet. Based on these mission requirements, the spectrometer will cover visible to MWIR band, with hyper spectral imaging ability and high sensitivity, and its structure should be very compact to meet the requirement of low mass and small volume design for deep space exploration payload.

The spectral characteristics, the "spectral fingerprint" of each substance, are the most effective and common means to identify minerals. At present, the spectral range of most imaging spectrometer for mineral detection is 0.4-2.5 μm. According to the experience of previous asteroid detection missions, expanding to MWIR band is more advantageous to distinguish the minerals having similar spectral absorption lines in visible to short wave infrared (SWIR) band, thus some new minerals can be discovered. On the other hand, considering the signal to noise ratio (SNR) would be reduced by the noise produced by thermal emission signal of optical-mechanical structure, the long wave edge of the spectrometer is set to be 5μm.

According to the analysis of several mineral samples in lab, the spectral sampling interval should be smaller for the substance whose spectral curve has some shallow absorption features, otherwise the spectral features can't be detected in the spectral signal of the instrument, or the position of the absorption feature will drift, which will influence the accuracy of the mineral identification. For the minerals have similar spectral characteristics whose spectral absorption lines are very close, the spectral resolution should be higher to improve the recognition rate of different minerals in similar rocks. At present, the understanding of the asteroid is limited. To identify more extraterrestrial minerals and find new types of minerals, the spectral resolution of the spectrometer should be higher. And considering the spectral range of the asteroid detection spectrometer and technical development level, the recommended spectral resolution is 5~10 nm.

The spectrometers for asteroid detection mission are usually carried on the orbiter, detecting the asteroid at a distance. For this kind of instrument, the design of the spatial resolution should consider the detection distance and the size of the asteroid. For the bodies of small diameter, the material distribution of the surface should be measured with high spatial resolution. And for the bodies that the probe flies by, the instrument of high spatial resolution would be advantageous because of the long detecting distance. Base on all these reasons, the instantaneous field of view (IFOV) of the spectrometer is 0.1 mrad, corresponding to the spatial resolution of 0.5m at the distance of 5km.

The observation radiance of visible and infrared spectrometer is depended on the albedo of asteroid and the observation angle relationship between the asteroid and the sun. The albedo is 0.13 according to NASA's near earth body observation plan, and the albedo of comet is about 0.05 or lower. For infrared band, the asteroid's surface temperature is generally acknowledged to be about 200K or lower. Thermal emission is mainly considered in MWIR band, and the energy detected in SWIR includes both reflected solar radiance and thermal emission radiance from target itself. The SNR of the previous deep space detection spectrometers is generally no less than 100, which can meet most scientific objectives. Therefore, the spectrometer for asteroid and comet detection should realize the SNR of better than 100 under the condition of low reflectivity and low temperature of the observation target.Its system requirements are shown as shown in Tab.1.

Tab.1 System requirements of Visible and Infrared Imaging Spectrometer

item	Technical Specifications
Spectral range	0.4-5μm
Spectral resolution	5nm@0.45~1.05μm, 10 nm@1.0~5μm
FOV	3.6°
SNR	100

spatial resolution	0.5 m@5 km

(1) Wide spectral coverage and compact design of the spectrometer

There are many unknown factors about the composition detection of small bodies, and scientists do not have experience data of the mineral types and its spectrum curves. More detailed science data can be obtained by the spectrometer with wider spectral coverage and higher spectral resolution for the identification and determination of substances compositions. Visible and infrared imaging spectrometer should cover from visible to medium wave infrared band, thus channel division, grating design and manufacturing are harder than traditional instrument. The optical system design should guarantee the performance with a very compact layout to meet the requirement of low mass and small volume of the deep space exploration payloads. By using a grating integrating the visible and infrared bands, folding the optical path, and other methods, the optical system can be very compact with few optical components, and can realize high grating diffraction efficiency, small spectral distortion and good imaging quality.

The optical system with all reflected mirrors is composed of a shafer telescope and an offner spectrometer, which covers all spectral range with one optical system without correction lens, dichroic plate and objective lens. The weight and volume can be strongly reduced by this design, as shown in Fig.5. The division of visible and infrared bands is realized by one grating with different groove densities in different regions, as shown in Fig.4.

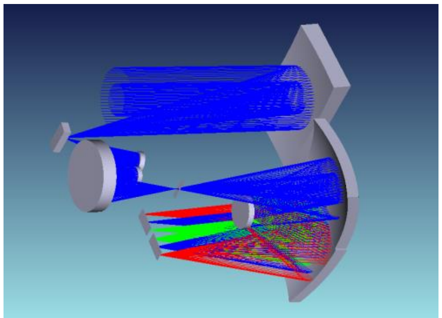

Fig.2. Optical system layout of visible and infrared imaging spectrometer

(2) High sensitivity spectral imaging technology

The detected energy of each spectral channels of the spectrometer is very week, due to the very low reflectivity and temperature of the deep space detection target, the small IFOV and dispersion principle of the spectrometer of high spatial resolution and high spectral resolution. Thus the requirement of the sensitivity of the instrument should be very strict. For the spectrometer working at MWIR band of 5 μm, the dark current noise of the detector should be reduced, and the noise produce by thermal emission of instrument should be limited to a negligible level. The thermal emission noise over the whole detecting link should be simulated. Low temperature design of optical system and detector cooling technology are adapted to control the noise effectively.

3.2 DESIGN OF THERMAL EMISSION SPECTROMETER

Based on the application demand and development trend of interferometric spectrometer on deep space detection, combined with the design points of wide range, high performance and light miniaturization of the interferometer spectrometer, An interferometric thermal emission spectrometer which target is Near Earth Asteroid 2016HO3is proposed. The scientific goal is to analyze the mineral composition and thermal properties of 2016HO3. Its system requirements are shown as shown in Tab.2.

Tab.2 System requirements of thermal emission spectrometer

item	Technical indicators
Spectral range	5-100μm
Spectral resolution	Less than 8 cm^{-1}
spatial resolution	Less than 10 m@5 km

The thermal emission spectrometer adopts the technology scheme of RC optical system and the time modulation Fourier interferometry and uncooled pyro electric detection. It can achieve the requirements of wide spectral range, high spectral resolution and high signal-to-noise ratio system. The composition of the thermal emission spectrometer system is shown in Fig.3. The target's thermal radiation signals are introduced into the interferometer through optical components. And then, it is modulated by the interference system. the modulated beam goes in to the aft-optical system and gathers on the detector. Interferograms are generated after photoelectric conversion. We can get the spectral information after data inversion.

The optical system of the thermal radiation spectrometer consists of ainput optical system, an interferometer system and an output optical system. It is shown in Fig.5. The Cassegrain telescope system is used in input optics to meet the adapting requirements of the interferometric system. He can effectively increase the input radiation energy. The core of the spectrometer is a time modulated, double cube cones and swinging arm interferometer. The interferometer mechanism has the advantages of simple structure, large rigidity and insensitivity to vibration, and is especially suitable for infrared spectrum. A self-compensating beam splitter is used in the interferometer system. The self-compensating beam splitter is a parallel plate, without the wedge angle and coating, and effectively avoids the problems of the traditional beam splitter and compensator, which is difficult to be coated. And the stability of the material of the infrared coating is poor. The wide spectrum dispersion of the wedge angle is also difficult to be compensated effectively. The highly stable metrology laser is used to realize motion control and interference signal sampling.

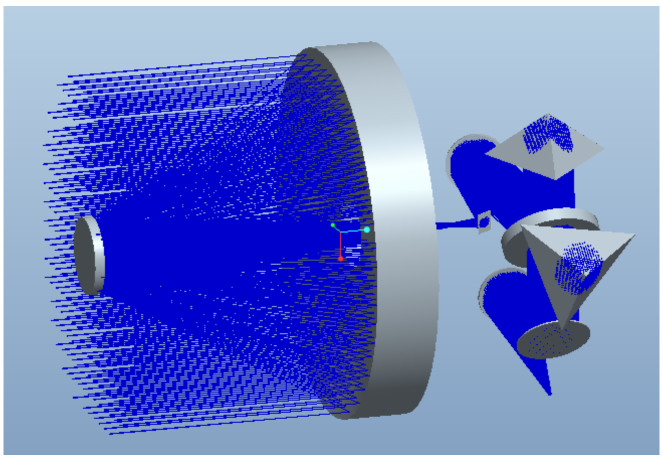

Fig.3 Optical system of thermal emission spectrometer

Spectrometer system with time modulated interferometric splitting scheme and pyro electric detector can detects spectral range of 5~100μm. The maximum optical path difference is±0.625mm. So the spectral resolution can reach 8cm-1.FOV is 2mrad to fit for the requirement of spatial resolution.

Based on the above requirements and working principles, the design of thermal emission spectrometer needs to break through the following key technologies:

（1）Short path and ultra-low speed of interference scan control technology

The maximum mechanical path difference of the spectrometer is only 0.15625mm.And the uniform scanning time is 1.8s. The scanning speed is very low and is hard to control. The spectrometer uses three loop(position, speed and acceleration) to control with feed forward links which is to improve the dynamic response of the system. A mathematical model of optical path scanning control system is constructed by dynamic simulation software. The nonlinear link in the system is introduced, and the output effect of the control algorithm after adding nonlinear links is simulated. Then the algorithm is fine-tuned according to the practical results, thus breaking through the control technology of short optical path and ultra-low speed interference scanning.

（2）High efficiency thermal emission interference splitter technology

The function of the interferometer is to modulate the measured beam. The key performance indexes are transmittance, modulation efficiency and scanning stability, which affect the signal-to-noise ratio of the system. The interferometer configuration and optical path optimization should be carried out to ensure high transmittance and high modulation efficiency of the interferometer. The loading and adjusting scheme of the interferometer also needs to ensure that no additional optical path difference is introduced.

（3）collection and processing technology of uncooled pyro electric weak signal technology

Aiming at the weak condition of infrared interference signal, the time constant of pyro electric detector and the detection conditions of all kinds of noises interference, the thermal emission spectrometer needs to detect and adjust the weak infrared interference signal and to reduce the noise of the circuit system and also to improve the anti-interference ability of the signal. At the same time, the high resolution ADC is used to meet the detection requirements of the large dynamic range interference signal. This technology does not rely on the hardware circuit. It calibrates the delay time, which needed to be compensated through data acquisition and processing. And then using algorithm can realize the synchronization of the signal. It can effectively improve the signal to noise ratio of the system

4. CONCLUSION

The discoveries of main belt comets (MBC) in early twentieth century have attracted great interests of the planetary society, as the water ice and other volatile rich MBCs are located in the main belt and thus may have played a fundamental role in supplying waters to the early Earth. Therefore, MBCs are very interesting and important candidate objects for near future deep space exploration missions. We first summarize the scientific objectives of visible and infrared spectrometers for a flyby mission. Then we propose the major technical specifications for the spectrometers, based on the optical and thermal properties of one of the major targets, 133P/Elst-Pizarro. Our proposed spectral coverage is from 0.4 to 50 μm, which is realized by two spectrometers covering 0.4-5 μm and 5-50 μm, respectively. Visible and infrared imaging spectrometer (VIIS) is a grating spectrometer covering 0.4 to 5 μm with a spectral resolution of 5 nm in the VIS/NIR band and 10 nm in the SWIR/MWIR band. The spatial resolution of the VIIS is 0.5 m at an observational distance of 5 km. The signal to noise ratio of the spectrometer is better than 100 using cryogenic optics technology. Thermal emission spectrometer (TES) is a time modulated Fourier transform spectrometer which covers 5-50 μmby one single interferometer. The spectral resolution of TES is 8 cm-1. The spatial resolution of TES is 10 m at an observational distance of 5 km.

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